"InAsP/InGaAs Materials Development for 2.1 μm Avalanche Photodiodes"

Phase II SBIR contract #N00014-93-C-0254

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Summary

Detailed measurements were carried out on our full InGaAs/InAsP APD structure optimized to detect light out to 2.1μm. Avalanche gains well above ten were confirmed independently, at Sarnoff as well as at Princeton University. Figures 1 and 2 contains some typical data from two 100 μm-diameter mesa devices. Note the gains of 10-40, dark currents near or below 1 μå at -10V and breakdown voltages of 30-35 volts. An 8 μm diameter single-mode fiber was used to scan light across the entire active region to check for edge breakdown. No enhanced gain was detected near the edges, thus validating our "p-substrate-mesa" approach to this device.

Figure 1 shows typical APD-like gain characteristics. The left axis indicates either dark- or photocurrent (in response to the indicated input light power fron a 1.6 μm laser) while the right axis displays net avalanche gain at a given bias. The data shown in figure 1 was taken directly from a chip that was probed on the original wafer. Figure 2 contains similar data from a chip that was cleaved from the wafer and mounted on a TO-46 type header. Note that both figures display a type of gain-saturation in that the increase. This could well be due to a defect-enhanced gain mechanism where avalanche breakdown initially takes place at defect sites which become depopulated at modest light levels. Further studies will be make on this effect. This could be one price paid for the directly deposited epitaxy scheme where no attempt is made to accommodate the lattice-mismatch between the substrate and layer. However, there are devices which do not exhibit this gain saturation effect so it may just be a yield issue. Reliability tests which will be carried out in the last months of our program should be telling here.

Another anomaly observed with these devices was a difficulty measuring the capacitance-voltage characteristics. We believe that the zinc-diffusion from the substrate has extended almost to the top layer of the devices so that it is always depleted. This long diffusion is due to the long (several hours) growth times required by the OMVPE system with its low (~1 μm/hr) growth rates. Proposed solutions are discussed in the next section.

These "breakthrough" results will be presented in a Post-Deadline paper at the Conference on Lasers and Electro-optics in Baltimore on May 25, 1995.

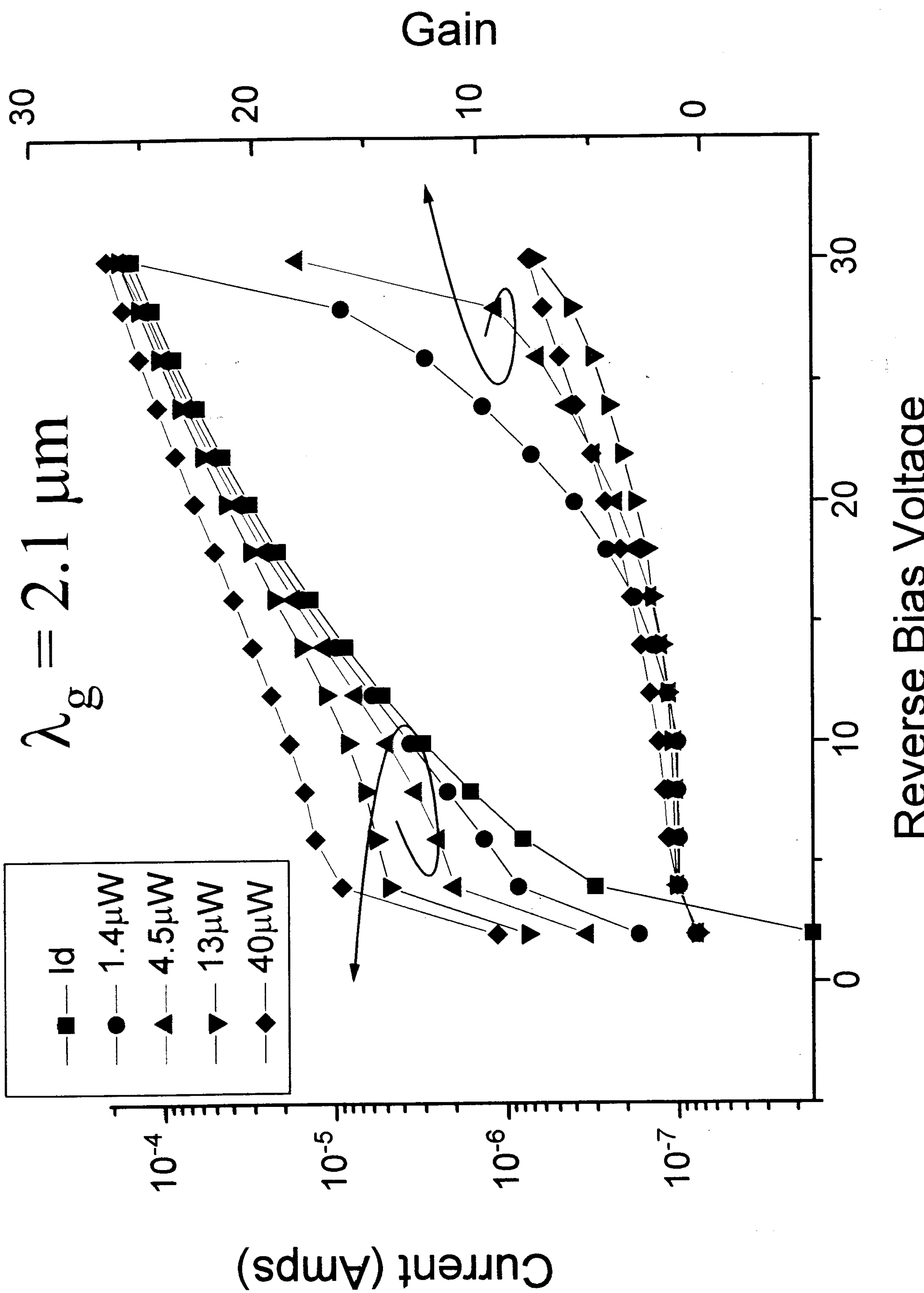
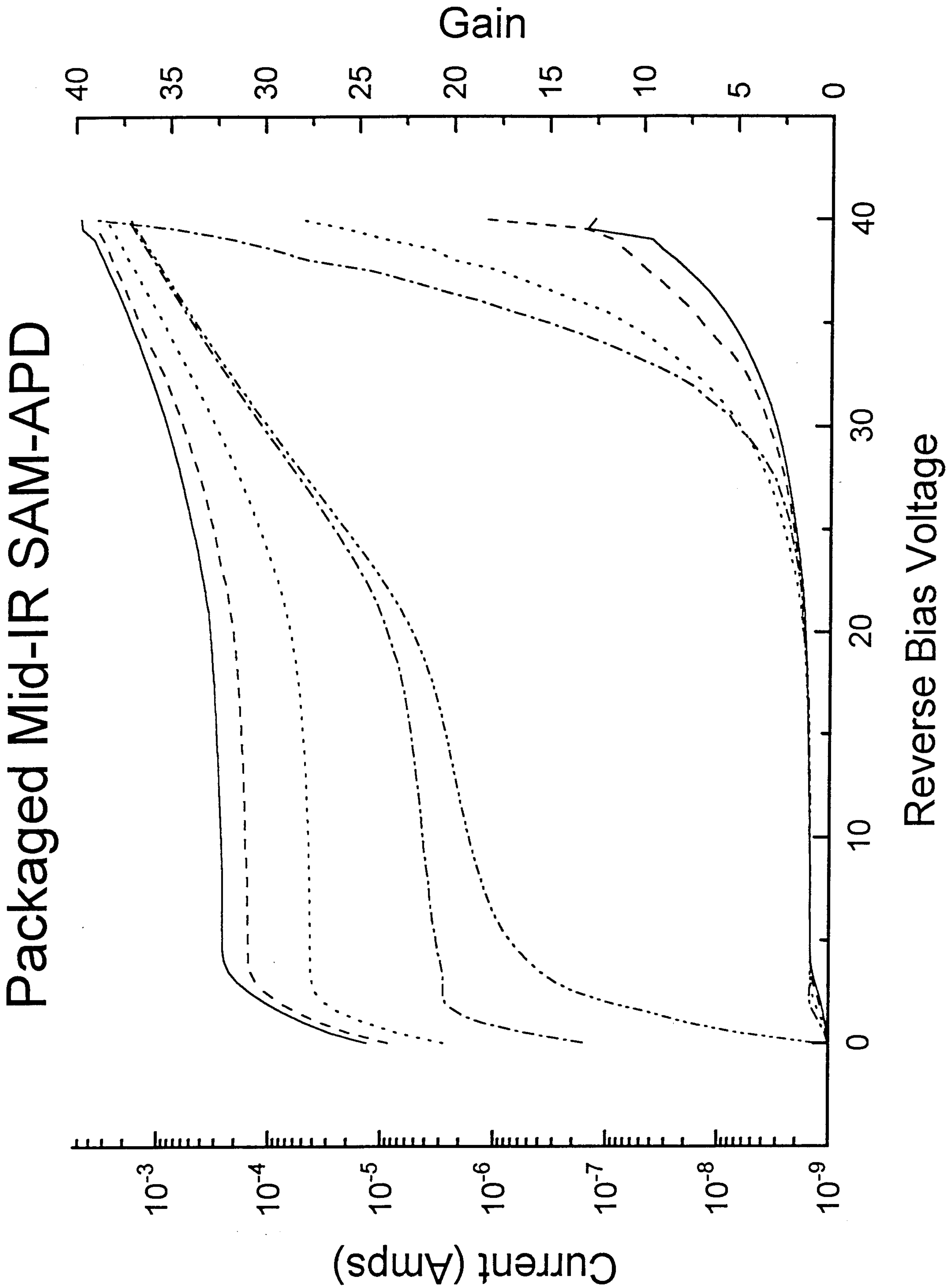

InGaAs SAM-APD
λg = 2.1 μm
Id
1.4μW
4.5μW
13μW
40μW
Gain
30
20
10
0
Current (Amps)
10-4
10-5
10-6
10-7
Reverse Bias Voltage
0
10
20
30

Figure 1.



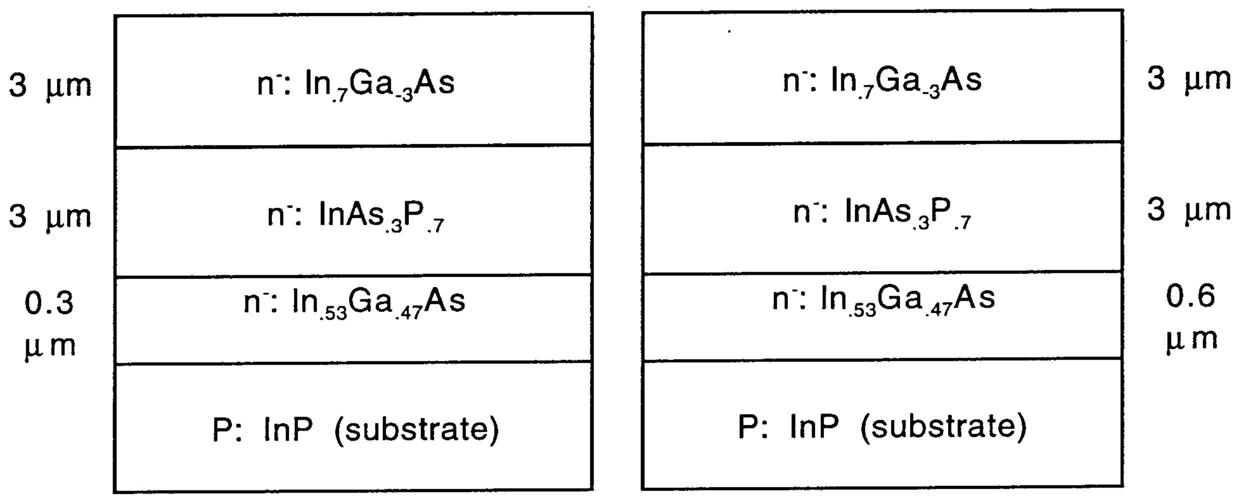
Packaged Mid-IR SAM-APD
Gain
40
35
30
25
20
15
10
5
0
Current (Amps)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0
10
20
30
40
Reverse Bias Voltage

Figure 2.

Next Quarter Plans

Figure 3 contains sketches of two proposed wafers that we will have fabricated and tested during the next quarter. The structure shown in figure 3a contains a 0.3 μm "buffer" layer of undoped $In_{.53}Ga_{.47}As$ while that of figure 3b contains a 0.6 μm thick buffer layer. Zinc diffuses about three times slower through $In_{.53}Ga_{.47}As$ than through InP and the presence of this buffer layer should keep the p/n junction location away from the top surface. We will also use two different substrate dopings: 3x10(18) and 5x10(17).

NEW 2.1 μm APD STRUCTURES



a) 0.3 μm buffer layer   b) 0.6 μm buffer layer

Each growth will have two "half" substrates: one doped Zn ~ 3×10^{18} and one Zn ~ 3×10^{17}

Figure 3.

Phase II Statement of Work

The overall technical objective of this program is to advance the state-of-the-art of InAsP/InGaAs materials development so that 2.1 μm APDs which presently do not exist and offer *ten times* the light detection sensitivity of anything now available can be made.

Specific technical objectives include:

- Development of the hydride vapor phase epitaxial (VPE) compositional grading technique to achieve a lattice mismatch ($\Delta a/a$) between the adjacent $InAs_yP_{1-y}$ and $In_xGa_{1-x}As$ epitaxial layers of about 0.13% or less.

- Development of innovative annealing techniques to reduce or eliminate lattice mismatch dislocations and thereby reduce the leakage currents of 2.1 μm Avalanche Photodiodes (APDs).

- Fabrication and testing of mesa type APDs for reliability. This will include development of polyimide passivation techniques as well as silicon nitride and silicon oxynitride using Plasma Enhanced Chemical Vapor Deposition (PECVD).

- Calibration of avalanche gain (M) vs. reverse bias (V) at temperatures of 250, 260, 270, 280, 290, and 300K.

- Deliver five APDs having the following characteristics:

Active diameter	100 μm
Room temperature spectral response	1.5 - 2.2 μm
Responsivity at unity gain condition	1.1 A/W @ 2.1 μm
Avalanche gain @ 0.98 of V_B	1 0
Shot noise current	<0.2 nA (rms) In a bandwidth of 100 MHz
Rise time/fall time	< 5 nsec
Mean time to failure (MTTF)	1×10^9 hours at 300K

Phase II Work Schedule

Task		Personnel	Months
1.	**Preliminary Design Work**	GO, MC	0 - 3
-	Overall mask design for 50,100, 200, and 500 μm diameter devices		
2.	**Materials**	GO, RM	1 - 9
-	Calibrate VPE reactor		
-	Etch pit studies for dislocations in InP substrates		
-	Optimize graded layers of VPE In(As,P)		
3.	**Study Avalanche Breakdown in $InAs_{.4}P_{.6}$**	RM, SF, GO	3 - 9
-	Grow VPE InAsP on InP with variable EPD		
-	Fabricate mesa APDs of various diameter		
-	Measure Id, Vg, M vs. diameter and EPD		
4.	**Fabricate APDs in InAsP**	E1, T1, RM	9 - 12
-	Optimize thickness/doping profile		
-	Determine optimum geometries		
5.	**Fabricate InGaAs/InAsP "SAM" APDs**	GO, RM, T1	12 - 20
-	Confirm thickness/doping profiles		
6.	**Device Characterization (SAM-APDs)**	GO, RM, T1	14 - 24
-	Measure I_d, V_g, C and M vs diameter		
-	Profile gain across diodes		
-	Measure pulse rise/fall time vs diameter		
-	Perform noise measurements		
-	Measure gain/bandwidth product		
7.	**Temperature Behavior**	Mc, E2	17 - 20
-	Dark current and gain from 250 to 300K		
-	Spectral cutoffs from 250 to 300K		
-	Noise properties from 250 to 300K		
8.	**Reliability Studies**	MC, GO, RM	19 - 24
-	Hermetically seal 100 μm devices		
-	Bias for 98% of voltage breakdown at 200°C		
-	Measure 20°C I_d, V_g, and M every 1000 hours		
9.	**Deliverables**	GO, RM, SF	24
-	Quarterly Reports		
-	5 APDs		
-	Final Report		
10.	**Phase III Effort**		24 -

(CLEO Postdeadline Paper - Committee #11)

A 2.1 μm Avalanche Photodiode

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Abstract

Avalanche gains beyond 20 were measured in 100 μm diameter $In_{0.7}Ga_{0.3}As/InAs_{0.3}P_{0.7}$ mesa-type photodetectors with light response out to 2.1 μm grown by OMVPE directly upon P-InP substrates without compositional grading. Dark currents below 1 μ A @ - 10 V and breakdown voltages of 30 - 35 volts were also observed.

D.S. Kim, et al "2.1 μm Avalanche Photodiode"

Summary

The concept of a "separate absorption and multiplication" region avalanche photodiode[1] (SAM-APD) has been extended out past 2 μm by using the $In_{0.7}Ga_{0.3}As/InAs_{0.3}P_{0.7}$ system. Figure 1 contains a sketch of the structure which utilizes no compositional grading. Although the two materials are lattice-matched to each other, there is nearly 1% mismatch with the P+InP substrate. The use of a heavily doped p-type substrate, along with the 100 μm diameter mesa structure beveled as shown, causes the depletion region to "bend away" at the edges and thus eliminates edge breakdown.

Figure 2 summarizes the device results. Gains of 10 - 30 were measured along with dark currents below 1 μ A @ - 10 V and breakdown voltages of 30 - 35 volts. The lack of enhanced gain at the mesa edge was confirmed by scanning an 8 μm diameter single-mode fiber across the device. In some cases, the gain was observed to decrease with increasing power, suggesting a gain saturation mechanism that could be due to the higher defect density associated with the large lattice-mismatch.

These devices would be particularly useful for near-infrared detection in the 2.0 - 2.1 μm spectral region for applications such as LIDAR, spectroscopy and windshear detection.

(1). S.R. Forrest "Gain-Bandwidth-Limited Response in Long-Wavelength Avalanche Photodiodes" IEEE J. Lightwave Technol. LT-2, 34 (1984)

(2). D.S. Kim, S.R. Forrest, G.H. Olsen, M.J. Lange, R.U. Martinelli and N.J. DiGiuseppe "Avalanche Gain in $InAs_yP_{1-y}$ ($0<y<0.3$) Photodetectors" Photonics Technology Letters (to be published).